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Experimental Study to Investigate Effect of Pitch Ratio and Number of Blades on Hydrodynamic Performance of Surface Piercing Propellers

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A B S T R A C T

Surface piercing propellers are special supercavitation propellers operating at free surface. These propellers are designed to have the best performance at the highest speed. The geometric parameters of the number of blades and the pitch ratio will significantly impact the critical advance coefficient range, ventilation and consequently the hydrodynamic performance of the propeller. Therefore, in this paper, the effect of two crucial parameters of pitch ratio and number of blades were experimentally studied in free surface water tunnel. After calibration and evaluation of uncertainty, two 5-bladed propellers with same section profile and pitch ratio of 1.5 and 1.4 used to investigate effect of pitch ratio. The results of two 5-blade and 6-blade propellers with same section profile and pitch ratio of 1.4 were compared. The immersion ratio was 40%, and the shaft inclination angle was zero. Results showed that increasing the pitch ratio increased the thrust and torque coefficients by 30%; while increasing the critical advance coefficient. Consequently that has led to the development of a full ventilation range and improved hydrodynamic performance of the propeller. In addition, by increasing the number of blades, at values greater than the critical advance coefficient, the thrust and torque coefficients were increased by 10%. However, the critical advanced coefficient changes were negligible. Comparing the results in the three-dimensional contours showed that with the change in the number of blades, by increasing the pitch ratio, the critical advance coefficient increased; which led to a further increase in efficiency.

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NOMENCLATURE

D	Propeller diameter (mm)	We_n	Weber number
EAR	Extended Area Ratio	Z	Number of blades
Fr_n	Froude number	γ	Shaft inclination angle (rad)
g	Acceleration of gravity($m.s^{-2}$)	η	Efficiency
h_t	Immersion depth (mm)	θ_R	Rake angle (rad)
I_T	Immersion ratio (%)	θ_S	Skew angle (rad)
J	Advance ratio	ϑ	Kinematic viscosity (m^2s^{-1})
J_{cr}	Critical adbance ratio	ρ	Density (kg/m^3)
K_Q	Torque quefficient	σ	Cavitation number
K_T	Thrust	Ψ	Yaw angle (rad)
n	Propeller rotational speed (rps)	T	Thrust
P	Pitch	Q	Torque
P/D	Pitch ratio	V_A	Propeller advance velocity (ms^{-1})
Re_n	Reynolds number		

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INTRODUCTION

Today, maritime transport is one of the most vital issues for the world economy. The importance of fast movement at sea has led to the development of the use of high-speed vessels, which achieving higher speeds in this type of vessel has always been an important issue for designers. In propulsion systems consisting of propellers, the propeller speed or diameter can be increased to achieve this goal. With increasing speed in submerged propellers, cavitation occurs which reduces the hydrodynamic performance of the propeller. To prevent this phenomenon, supercavitation propellers were invented. Increasing the diameter of conventional propellers is also associated with limitations; these include the shape of the stern and a proper distance between the tip of the blade and the stern; the minimum immersion depth can also be mentioned, which can increase the drag of the shaft attachments. Since the resistance of the attachments in a high speed vessel is considerable; therefore, reducing the resistance has a significant effect on increasing efficiency and reaching higher speeds with less energy consumption. To solve this problem, the U.S. Navy first used a propeller that the shaft and a half of the propeller were out of the water; thus, the resistance of the shaft and its accessories was eliminated. With shaft moving away from the body and the blades coming out of the water, there was no limit to increase the blade diameter. Also, under these conditions, the cavitation was replaced by the ventilation phenomenon; in such a way that the blade enters the water, splits the surface and draws air into the water; as a result, the movement of a part of the propeller in the air significantly reduces the skin friction and erosion caused by cavitation.

Surface piercing propellers are a type of supercavitation propellers that operate at the free surface. In this type of propellers, the cavitation is replaced by the ventilation phenomenon; as a result, the pressure at the suction surface of the blade is atmospheric. One of the main issues in surface-piercing propellers design is determining the hydrodynamic coefficients (thrust and torque) and efficiency. Experimental, semi-experimental, and numerical methods are commonly used to evaluate the hydrodynamic performance of surface piercing propellers. Despite the growth and development of numerical methods and their widespread use to predict propeller behavior, due to inaccuracies, experimental studies are still the best method to evaluate the performance of surface piercing propellers. There are still limited experimental data to describe the performance of the propeller under different operating conditions. The first comprehensive experimental study was conducted by Shiba [1] in which the effect of Weber number and parameters affecting ventilation in simple geometries was investigated. According to Shiba results, the Weber number 180 is known as the critical Weber number. This weber number was used to extend the test results to the prototype. At Weber numbers greater than 180, the effect of the Weber number on thrust and torque coefficients and the ventilation of the propeller is negligible. In a comprehensive experimental study, Olofsson [2] investigated the hydrodynamic coefficients and efficiency of a 4-blade surface piercing propeller (841-B) at different advance coefficients, shaft inclination angles, and yaw angles at immersion ratio of 0.33. In this study, the effect of Froude number and cavitation number on the hydrodynamic coefficients of the propeller was investigated. Based on the results, Froude number 4 is known as critical Froude number and the effect of Froude number on hydrodynamic coefficients in numbers greater than 4 is negligible.

Dyson [3] reported the result of four models of SPP. The test was performed on different propeller same diameter and pitch ratio and different sections, different number of blades and different shaft inclination angles. Accordimg to the results, the immersion ratio has significant effect on the results. Fernando et al. [4] examined the critical Weber number presented by Shiba [1], also considered the immersion ratio as one of the influential factors in the amount of Weber number. According to the results, the critical advance coefficient was expressed as a function of Weber number and pitch ratio and a regression formula was presented for it. Ferrando et al. [5] investigated the effect of pitch ratio, number of blades, immersion ratio, and shaft inclination angle on the performance of a SPP's. They used a systematic series of propellers with 4 and 5 blades to perform the test and to predict the hydrodynamic coefficients, the analytical relation s were presented. According to the results, due toan increase in pitch ratio, critical advance coefficient, thrust and efficiency increased. Peterson [6] conducted an experimental and numerical study of the effect of shaft inclination angle on the thrust of a surface piercing propeller. The results showed that changes in shaft inclination angle affect the thrust and thus the efficiency. Ghassemi et al. [7] focused on the immersion ratio, pitch ratio, and Weber number and examined the hydrodynamic characteristics of the surface piercing propeller with 3 and 6 blades using the boundary element method. The results showed that by increasing the pitch ratio, in addition to increasing the efficiency, the critical advance coefficient will also increase. Misra et al. [8] conducted an experimental study of 4-blade surface-piercing propellers with different cup-shaped sections. In this study, Weber numbers and immersion ratios were investigated. According to the results, the critical Weber number can be different for each propeller with an independent geometric shape. Yari and Ghassemi [9] investigated the effect of Weber number on hydrodynamic coefficients and changes in the ventilation pattern of a two-dimensional hydrofoil numerically using RANS method. The results showed that Weber number affects the changes in blade ventilation pattern, free surface spray, and blade pressure distribution. Then, Yari and Ghasemi [10] numerically investigated the cupped effect of the blade on the ventilation pattern of a blade of the 841-B propeller in two dimensions at an immersion ratio of 0.33 and a shaft inclination angle of zero degrees. The results showed the effect of the blade cup on increasing the maximum thrust, efficiency, and thickness of the propeller ventilation area. Seyyedi et al. [11] investigated the effect of shaft inclination angle and immersion ratio on the hydrodynamic coefficients of a 5-bladed surface-piercing propeller. They showed that as the immersion ratio increases, the thrust and torque coefficients will increase; but efficiency does not change. Figure 1 shows the loading postion of the surface piercing propeller blade during a fixed rotation [2].

The effect of immersion ratio on the performance of 5-bladed surface-piercing propeller (SPP-5.74) was numerically investigated by Rad et al. [12]. The results show that increasing the immersion ratio increases the thrust and torque coefficients and decreases the critical advance coefficient. Javanmard et al. [13] numerically studied the hydrodynamic coefficients and the pattern of the flow around the 841-B surface piercing propeller in different angular positions of the blade and in immersion ratio of 0.33. The results show that the thrust and torque coefficients of the propeller outside the water (zero degree angle position) have the lowest value and are maximized at 180 degree angle position. Alimirzadeh et al. [14] investigated the effect of immersion ratio and shaft angle on Olofsson's propeller. As the immersion ratio increases, the hydrodynamic coefficients increased and the efficiency decreased. Javanmard et al. [15] continued their research by numerically investigating the effect of shaft inclination angle on the hydrodynamic coefficients of the 841-B surface-piercing propeller in different angular positions. The results show that with increasing the shaft inclination angle, the thrust and torque coefficients increase; but the efficiency will decrease; also, the effect of shaft inclination angle on torque coefficient depends on the angular position of the blade. Seyyedi and Shafaghat [16] in a comprehensive study

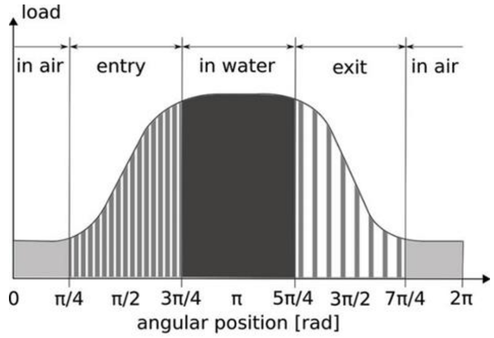


Figure 1. Loading position on the surface piercing propeller blade during one rotation (Olofsson [2])

reviewed experimental and numerical studies conducted by various researchers on surface-piercing propellers. After a comprehensive review of the various operating conditions, they stated that there are still many gaps in the available data and information; Because of the lack of sufficient data, error, and low accuracy of regression and semi-empirical relationships, it is not possible to provide a comprehensive assessment. Also, due to the existing complexities, a limited number of effective parameters have been studied and the effect of some effective parameters in propeller design has been ignored. Yousefi and Shafaghat [17] discussed changes in the ventilation pattern at different radial positions on a 5-bladed surface piercing propeller (Spp-5.74). The results show that at a constant advance coefficient, increasing the radius ratio reduces the thickness and length of the ventilation zone.

The first regression relationship was proposed by Ferrando et al. [5] Although Ferrando relations can to some extent predict the trend of changes in hydrodynamic coefficients, they cannot accurately determine the value of the coefficients; Because of the lack of comprehensive study of geometric and physical parameters affecting propeller performance, these relationships are not very accurate in many operating conditions. Therefore, Seyyedi et al. [18] by conducting additional tests and considering the results of experimental research of previous researchers, while developing a database of surface-piercing propellers, provided more accurate relationships. The results of the present experimental study were also compared with the relationships presented by Seyyedi et al. [11] due to the limitations of the experimental study and review in previous work some parameters affecting the performance of surface-piercing propellers such as pitch ratio and the number of blades need to be studied. The study of these two parameters requires a change in the geometry of the propeller, which caused some difficulties due to the production equipment. Therefore, due to the lack of complete experimental research in this field, in this study, the effect of important parameters of pitch ratio and number of blades has been investigated experimentally. In this regard, in order to investigate the effects of pitch ratio, two 5-bladed propellers with pitch ratio of 1.4 and 1.5 have been used; Also, to investigate the effects of the number of blades, two propellers with 5 and 6 blades with the same section profile and pitch ratio have been used. It is worth mentioning that to evaluate the performance of these propellers, in addition to examining the hydrodynamic coefficients, changes in the critical advance coefficient range have also been considered.

METHODS AND MATERIALS

Parameters affecting propeller performance

Parameters affecting the performance of the surface-piercing propeller include two categories of geometric and physical parameters. Geometric parameters such as pitch (*P*), diameter (*D*), expanded area ratio (*EAR*), number of blades (*Z*), rake angle (θ_r), skew angle (θ_s), yaw angle (ψ), shaft inclination angle (γ), immersion ratio (*I*), and blade thickness (*t*). Physical parameters also include advance ratio (*J*), Reynolds number (*Re*), cavitation number (σ), Weber number (*We*), and Froude number (*Fr*). Figure 2 shows the concepts of shaft inclination angle and yaw angle as well as the immersion ratio. The physical parameters are also defined as follows:

$$F_n = \frac{nD}{\sqrt{gD}}$$

$$J = \frac{V_A \cos(\psi)}{nD}$$

$$W_n = \frac{nD}{\sqrt{\sigma_k/\rho D}} \tag{1}$$

$$Re = \frac{nD^2}{v}$$

where V_A is the propeller advance velocity, n is the propeller speed, σ_k is the water capillary constant, and v is the kinematic viscosity of water.

Hydrodynamic coefficients of propellers

Thrust and torque along with efficiencies are typically used to evaluate propeller performance (Equation (2)).

$$k_T = \frac{T}{\rho n^2 D^4}, \quad k_Q = \frac{Q}{\rho n^2 D^5}, \quad \eta = \frac{J}{2\pi} \times \frac{k_T}{k_Q} \tag{2}$$

k_T is the thrust coefficient, k_Q is the torque coefficient, η is efficiency, T is the propeller output thrust, Q is the propeller torque and ρ is the water density.

Experimental setup and calibration

For experimental studies of surface-piercing peopeller, free surface water tunnels or towing tanks are typically used. Due to the lower cost of testing in free surface water tunnels and the possibility of easier observation of fluid phenomena, free surface water tunnels are considered as one of the most widely used equipment to study the hydrodynamic behavior of surface piercing propellers. In this study, the free surface water tunnel of Babol Noshirvani University of Technology was used (Figure 3). The general characteristics of the water tunnel are presented in Table 1 (Seyyed et al. [16]).

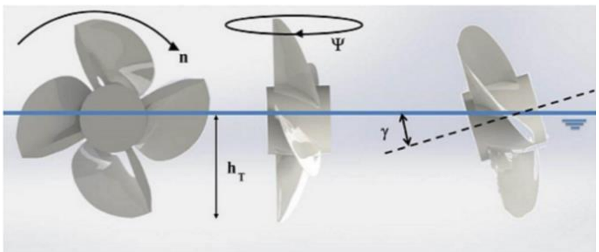


Figure 2. Yaw angle, shaft inclination angle, and immersion ratio (Seyyedi et al. [11])

Figure 3. Free surface water tunnel of Hydrodynamics and Marine Propulsion Research Lab. in Sea-Based Energy Research Group, Babol Noshirvani University of Technology

Table 1. General specifications of free surface water tunnel of Noshirvani University of Technology in Babol (Seyyedi et al. [16])

Test section	Length (m)	2
	Height (m)	0.3
	Width (m)	0.3
Nozzle	Contraction area ratio	9 to 1
Pump	Power (kW)	45
	Rotation speed (rpm)	1450

A two-component dynamometer was used to extract the value of thrust and torque of the propeller. It is possible to change the shaft inclination angle and the immersion ratio in this dynamometer (Figure 4).

Thrust and torque sensors have a weight capacity of 100 and 50 kg, respectively (Figure 5). Also, a view of the propeller installation in the tunnel is shown in Figure 6.

Figure 4. Overview of dynamometer with model propeller in the test section

Figure 5. Location of thrust and torque sensors

Figure 6. View of the impeller installed in the test section

Labview control and monitoring software has been used to process and record the data received from the sensors. An example of a user interface can be seen in Figure 7. The equipment is first calibrated to ensure accurate measurement. A mercury manometer is used to measure the flow rate through the test section. In order to calibrate the manometer, the results were compared with the data measured by the ultrasonic flowmeter manufactured by Flexim (Fluxus ADM 6725). The results of velocity uncertainty analysis in the test section with 6 repetitions are shown in Table 2. In order to evaluate the accuracy of the results of thrust and torque measurements, the tests were performed in 5 replications. Table 3 shows an example of calibration data and uncertainty analysis for a 5-bladed propeller with a pitch ratio of 1.4, in two coefficients of advancement, zero shaft angles, and 40% immersion ratio.

Specifications of model propellers

Due to the fact that the pitch ratio and the number of blades are considered as the main variables of the experiment, in this study, three propellers have been used.

Table 2. Mean uncertainty analysis for velocity calibration in tunnel test section

Test .1 (ms^{-1})	Test .2 (ms^{-1})	Test .3 (ms^{-1})	Test .4 (ms^{-1})	Test .5 (ms^{-1})	Test .6 (ms^{-1})	Average speed (ms^{-1})	Standard deviation (S)	Mean uncertainty (U_A)
2.806	2.790	2.760	2.721	2.725	2.696	2.749	0.0425	±0.0173

Table 3. Mean uncertainty analysis for thrust and torque measurements

	Advance Coeff. (J)	Test. 1	Test .2	Test. 3	Test .4	Average	Standard Deviation (S)	Mean uncertainty (UA)
K_t	0.5	0.06789	0.06983	0.06927	0.06817	0.06879	0.00091	±0.00046
	0.9	0.08649	0.07830	0.08202	0.09227	0.08477	0.00602	±0.00301
K_q	0.5	0.01404	0.01362	0.01417	0.01387	0.01392	0.00024	±0.00012
	0.9	0.01513	0.01573	0.01726	0.01602	0.01604	0.00090	±0.00045

To evaluate the changes in pitch ratio, two 5-bladed propellers with fixed diameter have been used and to study the changes in the number of blades, two propellers, one with 5 blades and the other with 6 blades with equal pitch ratio were used (Figures 8 and 9). The specifications of the propellers are given in Table 4.

The tests were performed in the range of advance coefficient of 0.4-1.2, immersion ratio of 40%, and also zero shaft inclination angles (Table 5).

Test conditions

Before testing surface-piercing propellers, the range of Reynolds, Froude, and Weber dimensionless numbers should be considered to evaluate the possibility of generalizing experimental results. The results of Olofsson's study in 1996 showed that at Froude numbers above 4, the cavities were created by ventilation reach their final shape and the results can be considered independent of Froude number. Also, according to Shiba [1] experimental results, if the Weber number is considered greater than 180, then it will not affect the critical advance coefficient and the ventilation phenomenon. Of course, the critical Weber numbers have also been declared by Ferrando [5] and Misra et al. [8] to be more than 180. In the present study, the rotational speed of the propeller is 34.8 (rps).

$$Fr = n \times \sqrt{\frac{D}{g}} \geq 4$$

$$We_n = \sqrt{\frac{n^2 \times D^3}{\kappa}} \geq 180 \quad (3)$$

$$Re_n = \frac{\rho \times n \times D^2}{\mu} \geq 5 \times 10^5$$

Validation

To validate the experimental results, a comparison between the present work and the experimental results of (Olofsson [2]) was performed. The diameter of the Olofsson propeller is 250 mm. Due to the limitations of the test section, a propeller with a diameter of 125 mm (scale 0.5) was used (Figure 10 and Table 6).

Figures 11 and 12 show a comparison of the obtained thrust and torque coefficients with Olofsson 's work at a Froude number of 2 (V = 2.21m / s). As can be seen, the experimental results obtained from the free surface water tunnel are with Olofsson's results. Ofcourse, the slight discrepancy that exists in the high advance coefficients is independent of the test equipment; it can be due to errors in the construction of the propeller, inadequate polishing of the surface, and also changes in the dimensions of the propeller.

Table 4. Specifications of model propellers

Parameter	Symbol	5 bladed-A	5 bladed-B	6 bladed
Diameter (mm)	D	125	125	125
Hub diameter (mm)	d	22.74	22.74	22.74
Hub–diameter ratio	d/D	0.182	0.198	0.182
Pitch (mm)	P	182	186	182
Number of blades	Z	5	5	6
Pitch–diameter ratio	P/D	1.4	1.5	1.4
Direction of rotation		RH	RH	RH

Table 5. Specifications and range of changes of test variables

Parameter	Symbol	Value
Immersion ratio (%)	I_T	40
Shaft inclination angle (°)	γ	0
Advance coefficient	J	0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0,1.2

RESULTS AND DISCUSSION

In this section, the effect of pitch ratio on thrust and torque coefficients, efficiency, and critical advance coefficient range is first investigated; then, the effects of

Figure 10. Model propeller made based on the characteristics of Olofsson [2] propeller with a diameter of 125 mm

Table 6. 4-bladed propeller specifications for validation

Parameter	Symbol	Value
Diameter (mm)	D	125
Hub diameter (mm)	D	42.5
Number of blades	Z	4
Pitch–diameter ratio at 0.7 radius	P/D	1.24
Extended Area Ratio	EAR	0.58
Shaft inclination angle (°)	γ	0
Immersion ratio (%)	I_T	33
Direction of rotation		RH

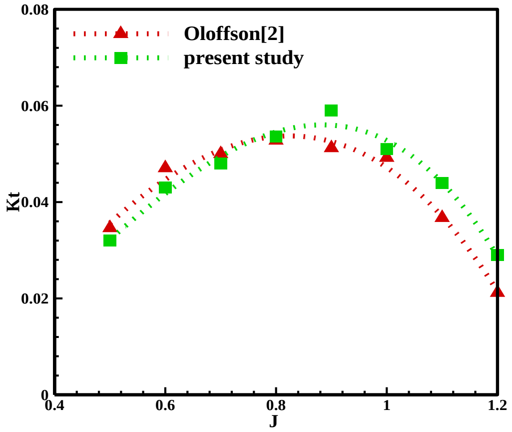


Figure 11. Comparison of thrust coefficient in the present work with Olofsson experimental results (Olofsson [2])

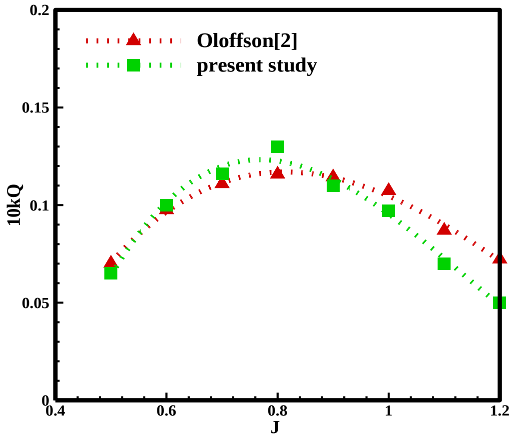


Figure 12. Comparison of torque coefficient in the present work with Olofsson experimental results (Olofsson [2])

the number of blades on the propeller performance are evaluated. It is noteworthy that simultaneous evaluation of the effects of pitch ratio and the number of blades on propeller performance is important; therefore, to evaluate and investigate the simultaneous effect of pitch ratio and the number of blades on the hydrodynamic performance of the propeller, the results are presented in the form of diagrams and three-dimensional contours. As mentioned in introduction, in order to facilitate the determination of hydrodynamic coefficients in design of surface-piercing propellers, in some studies, semi-empirical relationships have been proposed, among which we can mention the relationships provided by Seyyedi et al. [16]. It is important to note that in addition to using their experimental test data, they also used relationships and data from past empirical studies to complete the database and provide relationships; therefore, these relationships can be considered as the most accurate relationships available. In the final section, to evaluate the accuracy of the relationships presented by Seyyedi et al. [16], the experimental hydrodynamic coefficients obtained for 5-blade impellers are compared with the calculated results of semi-empirical relationships.

Pitch ratio

When the blade hits the water, two vertical and lateral forces are applied to it. Increasing the pitch ratio increases the angle of attack; as the angle of attack increases, the lift force and consequently the thrust of the propeller will increase. Changing the thrust changes the propeller efficiency. The length of the ventilation line will decrease as the pitch ratio increases. As the length of the ventilation line decreases, the advance coefficient decreases; in this case, complete ventilation occurs sooner. In other words, the propeller reaches a critical point at higher advance coefficients.

Figure 13 shows a diagram of the thrust coefficient of two propellers. According to obtained results, the maximum values of 5-bladed propellers with pitch ratio of 1.4 and 1.5 were 0.09 and 0.12, respectively. Therefore, with increasing pitch ratio, the maximum thrust coefficient increases by 33%. Also, the critical advance coefficient corresponding to each of the maximum thrust values will be equal to 0.7 and 0.8, respectively. Comparison of the results shows that increasing the pitch ratio in the fixed diameter will increase the maximum thrust coefficient and as a result the thrust produced by the propeller. Also, the investigation of the critical advance coefficient of two propellers showed that increasing the pitch ratio increases the critical advance coefficient and increases the complete ventilation range.

Figure 14 shows the torque coefficients for two 5-bladed propellers. According to the results, the maximum torque coefficient is equal to 0.3 and 0.23 for propellers with pitch ratios of 1.5 and 1.4, respectively. By increasing the pitch ratio at a constant diameter, the maximum torque coefficient will increase by 30%. According to Figure 15, increasing the pitch ratio after the

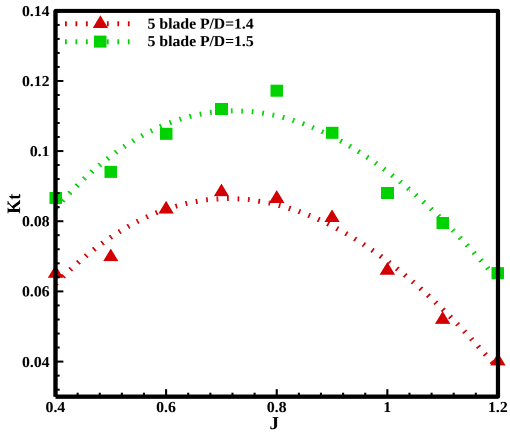


Figure 13. 5-blade impeller thrust coefficients changes

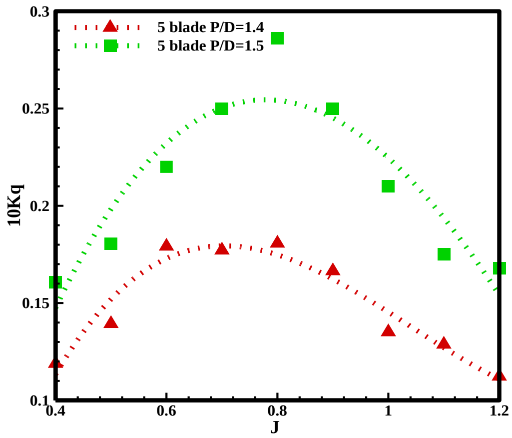


Figure 14. 5-blade impeller torque coefficients changes

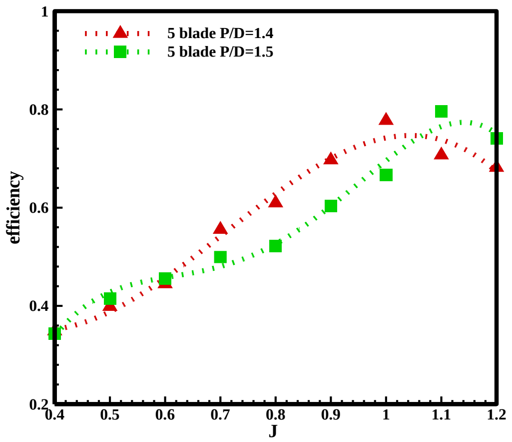


Figure 15. 5-blade impeller efficiency changes

critical advance coefficient increases the propeller efficiency. At lower pitch ratios and lower than critical advance coefficients, the efficiency is lower.

Number of blades

In examining two propellers with different number of blades, the performance depends on the Froude number as well as the even or odd number of blades. Propellers with even number of blades have a symmetrical operation; in such a way that the conditions of the blades entering the water are similar to the conditions of the blades leaving the water. Whereas for propellers with odd number of blades, due to the operating conditions, the forces and torques applied to the blades as well as the phenomena that occur will be asymmetric in terms of entering and leaving the water. The important point is that in the symmetric state the thrust and torque forces do not change significantly and instantaneous changes in thrust and torque compensate for each other. Therefore, according to Figures 16 and 17, the oscillating forces are reduced and the values of thrust and torque until the critical value is less than the same 5-bladed propeller. Even or odd number of blades only affects the oscillating forces on the propeller. In a 6-bladed propeller, the cord length is reduced compared to a 5-bladed propeller; Therefore, another reason for this behavior can be the different distances between the blades and different lengths of the chord. This abnormal behavior at the beginning of the ventilation affects the length of the ventilation area and changes the range of the critical advance coefficient. According to Figure 18, as the length of the chord decreases, the length of the aeration zone also decreases, which increases the critical advance coefficient.

Consideration of pitch ratio and number of blades

Figures 19 to 21 compare the effects of pitch ratio and number of blades on the performance coefficients and the critical advance coefficient range of the propeller. As can be seen, compared to the number of blades, the pitch ratio has a significant effect on the thrust coefficient; in such a way that for a propeller with a greater pitch ratio, the critical advance coefficient becomes greater and the maximum efficiency occurs at higher critical advance

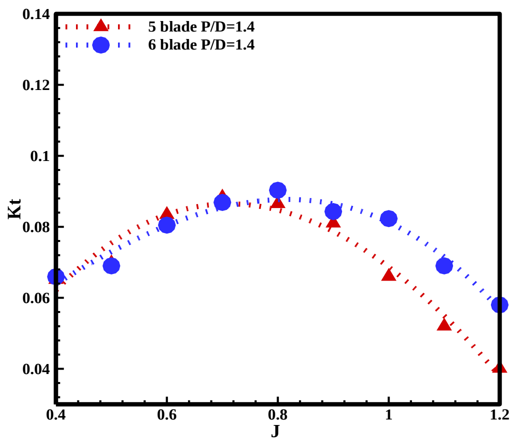


Figure 16. Thrust coefficient of 5-blade and 6-blade propellers

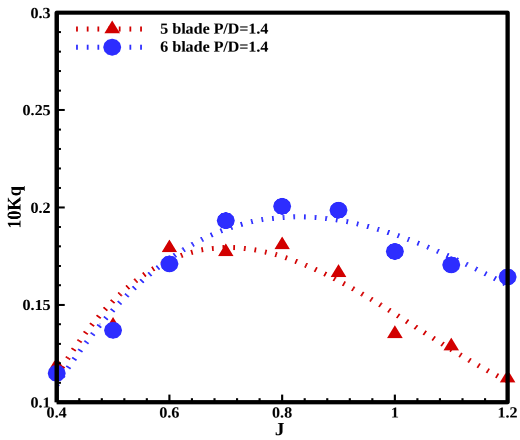


Figure 17. Torque coefficient of 5-blade and 6-blade propellers

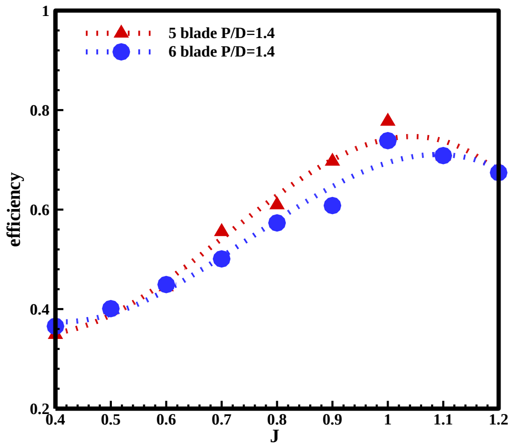


Figure 18. Efficiency of 5-blade and 6-blade propellers

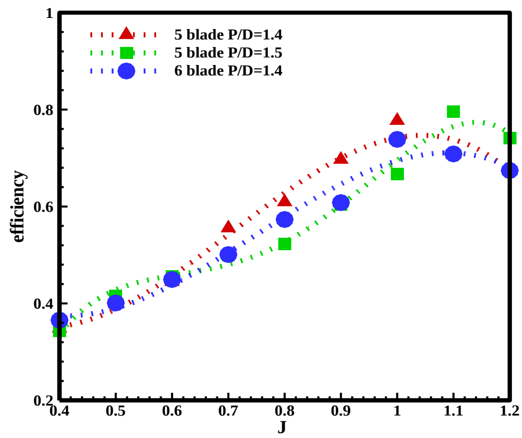


Figure 21. Efficiency of 5-blade A and 6-blade propellers

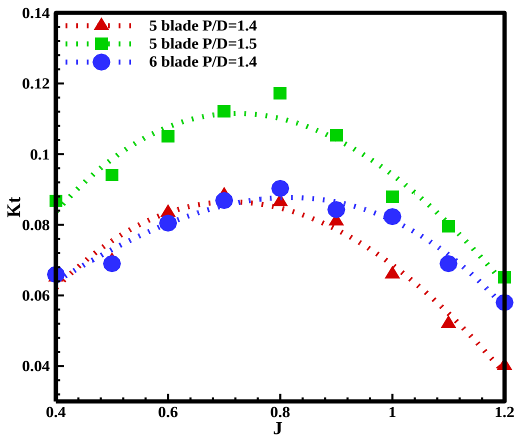


Figure 19. Trust coefficient of 5-blade A and 6-blade propellers

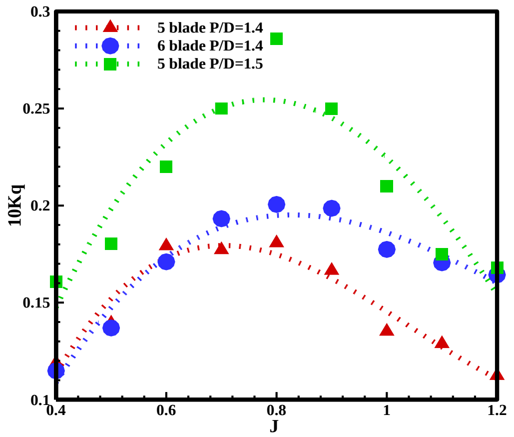


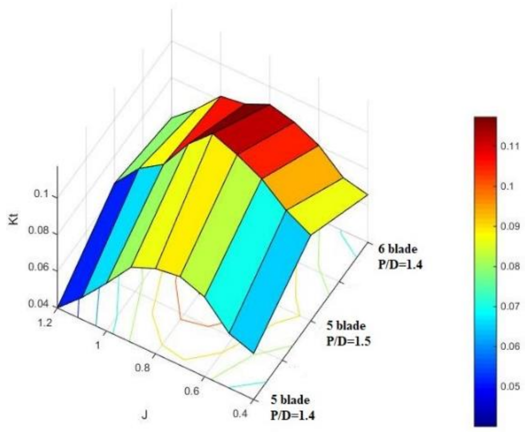
Figure 20. Torque coefficient of 5-blade A and 6-blade propellers

coefficients. According to the results, if increasing the thrust force is a priority, increasing the number of blades will be more effective. However, if the increase in torque does not cause a problem in the design process and the goal is to increase efficiency, a pitch ratio change should be used.

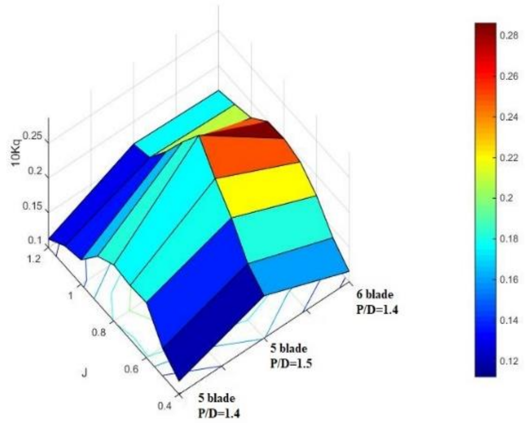
In order to more accurately study the simultaneous effects of pitch ratio and number of blades, three-dimensional contours have been used (Figure 22). As can be seen, changes in hydrodynamic coefficients are more affected by the pitch ratio; As a result, in all contours, the thrust and torque coefficients will increase more dramatically due to the change in pitch ratio. Comparison of the results of 5 and 6 bladed propellers with a pitch ratio of 1.5 shows that the efficiency of the 5 bladed propellers is lower until it reaches the critical point; but by passing the critical point, the efficiency of the 5-bladed propeller will grow more than that of the 6-bladed propeller. This result is due to the further increase of the torque coefficient in the range of advance coefficients lower than the critical value and also the inverse relationship of the torque coefficient with the efficiency. In other words, by increasing the torque coefficient or decreasing the thrust coefficient, the efficiency will decrease.

Comparison of results with regression relationships

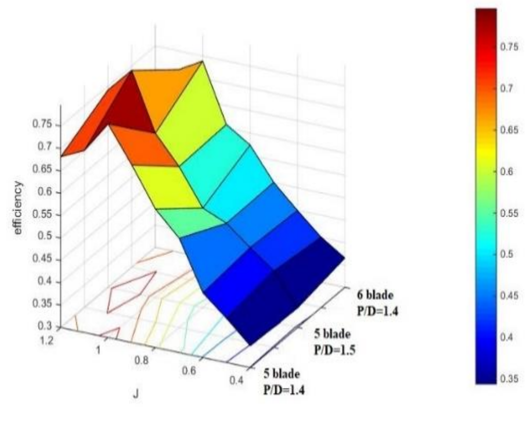
As shown in Figures 23 and 24, although Seyyedi's semi-empirical relationships can predict the trend of changes in hydrodynamic coefficients and critical advance coefficients range for both thrust and torque, these relationships are not accurate enough. Because, to accurately evaluate the performance of surface-piercing propellers, complex fluid phenomena must be considered. Therefore, achieving comprehensive relationships to



(A)



(B)



(C)

Figure 22. Three-dimensional contours: thrust coefficient (A), torque coefficient (B) and efficiency (C)

accurately determine the hydrodynamic coefficients of surface piercing propellers is almost impossible, and the existing relationships can be used to identify the overall performance of each propeller. As a result, an experimental study has always been the most important method to ensure the performance of surface piercing propellers.

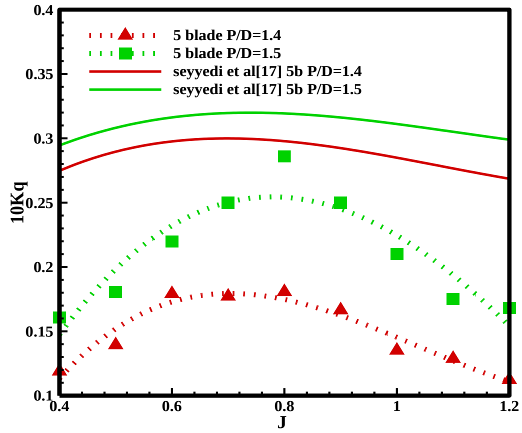


Figure 23. Comparison of torque coefficients obtained from regression relationships (Seyyedi et al. [16]) with the results of the present work

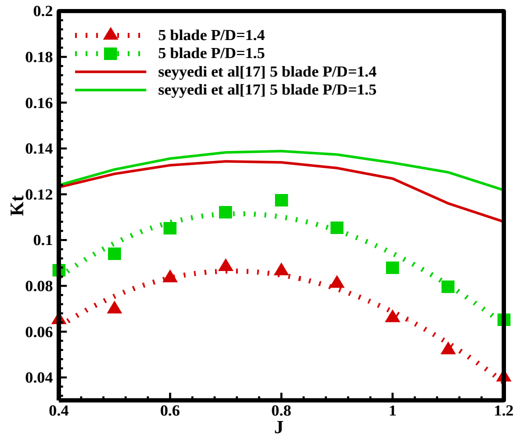


Figure 24. Comparison of thrust coefficients obtained from regression relationships (Seyyedi et al. [16]) with the results of the present work

CONCLUSION

In this study, the effects of pitch ratio and number of blades on hydrodynamic coefficients (thrust and torque), efficiency, and critical advance coefficient range of surface-piercing propellers were experimentally investigated. For this purpose, two 5-bladed propellers 5A and 5B with equal diameter and with a pitch ratio of 1.4 and 1.5, respectively, along with a 6-bladed propeller with a pitch ratio of 1.4 were used. The section profiles of the propellers are considered the same. The range of advance coefficient changes was (0.4-1.2) and the immersion ratio was 40%. Experimental tests were performed in a free surface tunnel. In this study, while examining the mentioned parameters separately and simultaneously in the form of diagrams and two and three-dimensional contours, the obtained experimental results are compared with the results obtained from the regression relations of Seyyedi's work as discussed above. The most important results can be summarized as follows:

- At a fixed diameter, with increasing propeller pitch ratio, the propeller maximum thrust and torque increase, and the critical advance coefficient occurs at higher values.
- In the fixed pitch ratio, at coefficients smaller than the critical advance coefficient, with increasing number of blades, the thrust and torque coefficients for the 6-bladed propeller are lower than the same value for the 5-bladed propeller.
- At coefficients greater than the critical advance coefficient, the hydrodynamic coefficients of the 6-bladed propeller will be greater than the same values of the 5-bladed propeller.
- The maximum values of the hydrodynamic coefficients in the 6-bladed propeller are approximately equal to the 5-bladed propeller, and the only difference is in the position of the maximum efficiency, which will occur in the 6-bladed propeller at a higher advance coefficient.
- Comparison of the obtained experimental results with semi-empirical relationships showed that regression relationships are not accurate enough despite correctly predicting the critical advance coefficient range. Because to accurately evaluate the performance of surface-piercing propellers, complex fluid parameters and phenomena must be considered.

As a result, it is almost impossible to achieve comprehensive relationships to accurately determine the hydrodynamic coefficients of surface-piercing propellers, and the existing relationships can be used to identify the overall performance of each propeller as well as the critical advance coefficient range; therefore, an experimental study has always been the most important method to ensure the performance of surface piercing propellers.

As a practical result, the following can be mentioned:

- Pitch ratio changes are used when thrust factor and efficiency parameters are important.
- When the thrust coefficient parameter is not important and the efficiency is important, the number of blades changes are used.
- When there is a need to increase speed of boat at higher speed values, pitch ratio changes are used.
- The use of regression relations is the last choice due to the low accuracy compared to the experimentally test.

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Persian Abstract

چکیده

پروانه‌های نیمه‌مغروق نوع ویژه‌ای از پروانه‌های سوپرکاویتاسیونی هستند که در سطح آزاد عمل کرده، طوری طراحی می‌شوند که بهترین عملکرد و بیشترین راندمان را در بالاترین سرعت داشته باشند. به منظور ارزیابی درست و دقیق عملکرد این دسته از پروانه‌ها و نیز تعیین ضرایب هیدرودینامیکی، شناخت دقیق پارامترهای موثر هندسی و فیزیکی بسیار مهم است. پارامترهای هندسی تعداد پره و نسبت گام به دلیل تغییر در زاویه حمله و تغییرات طول کورد تأثیرات زیادی بر روی جابجایی محدوده ضریب پیشروی بحرانی، پدیده هواگیری و به دنبال آن عملکرد هیدرودینامیکی پروانه خواهد داشت. در این پژوهش به منظور بررسی تأثیر نسبت گام دو پروانه ۵ پره با پروفیل مقطع یکسان و نسبت گام‌های ۱/۵ و ۱/۴ مورد بررسی قرار گرفته‌اند. جهت بررسی تاثیرات تعداد پره از یک پروانه ۶ پره با پروفیل مقطع مشابه و نسبت گام ۱/۴ استفاده شده است. نسبت مغروقیت ۴۰ درصد و زوایه انحراف شفت صفر می‌باشد. با بررسی نتایج، افزایش نسبت گام سبب افزایش ۳۰ درصدی مقادیر ضریب تراست و گشتاور شده، ضریب پیشروی بحرانی را افزایش می‌دهد. افزایش ضریب پیشروی بحرانی سبب توسعه محدوده هوادهی کامل شده؛ در بهبود عملکرد هیدوردینامیکی پروانه و در نتیجه شناور تندرو تأثیرگذار خواهد بود. همچنین با افزایش تعداد پره، در مقادیر ضریب پیشروی بیشتر از بحرانی یک افزایش ده درصدی در مقادیر ضرایب تراست و گشتاورایجاد شده ضریب پیشروی بحرانی به میزان بسیار ناچیزی به جلو رانده می‌شود.